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May 1985

BIOCYBERNETIC ANALYSIS OF A HYBRID WORKLOAD MODEL

Phase I Final Report
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Biocybernetic measures -heart rate inter-beat interval (IBI) and event-related brain potential (ERP)- were used to provide converging operations to refine a hybrid model of attention and workload. Two experiments using the psychological refractory period paradigm were conducted with stimulus-response uncertainty and inter-stimulus interval (ISI) as manipulations of workload. Reaction time was influenced by uncertainty and ISI; IBI standard deviation and spectral data were influenced only by uncertainty; preliminary analysis of ERP showed N200 amplitude to be influenced by uncertainty and ISI. These results were related to a hybrid processing model formulated by Kantowitz and Knight (1976).

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The Information-Processing Approach

There are several crucial assumptions shared by researchers who adopt the information-processing approach to the study of human behavior. The most important assumption is that behavior is determined by the internal flow of information within a person. Since this information flow is internal and invisible, special techniques and methodologies are used to allow inferences about this postulated information flow. But all these techniques share the basic goal of information-processing research which is to map internal information pathways.

The information-processing approach uses techniques that are in many ways similar to those used by engineers designing large systems. The human is regarded as a complex system and experimental psychologists try to discover what happens inside the "black box." However, engineers have a considerable advantage since they can insert probes and meters within their black boxes; the psychologists cannot. It is here that psychophysiology comes to the aid of the behavioral psychologist, using measures like brain waves to help peer into the black box. At present this technique cannot yet plot the hypothetical information pathways inside the human. Thus, the effort to understand internal information flow proceeds primarily by testing alternate representations based upon different arrangements of sub-systems with different properties. Yet, the rapid progress in psychophysiology suggests that in the near future behavioral measures may be subordinated to neural and autonomic correlates of behavior. For now, however, we believe that both behavioral and biocybernetic measures must complement each other in efforts to provide converging operations that jointly map mental processes.

It is not sufficient to create a model that will duplicate the behavior of humans, although this is of course a necessary requirement for any information-processing model. A female singer and a tape recording made with the proper brand of tape might both be able to shatter a slender crystal goblet, but no one would claim that this duplication of behavior proves that the singer and the tape recorder produce auditory signals by the same internal processes. Thus, the information-processing theorist must duplicate not only behavior but also the internal patterns of information flow before an acceptable explanation of human thought and action can be found.

Information-processing models differ in the number and arrangement of sub-systems. Many possible arrangements are reasonable so that each theorist must try to show how their model is superior to other competing models. There is seldom complete agreement about which model is best and psychophysiological theories are not yet sufficiently advanced to permit reliable evaluation of competing theories that share common structure and assumptions. (Psychophysiology can distinguish among different classes of behavioral models but this is a relatively modest achievement compared to the potential of psychophysiology.) The typical information-processing model represents the human cognitive system as a series of boxes connected by an assortment of arrows. The boxes represent sub-systems that perform different functions and processes that route information to and from the various boxes. Each box represents a generalized kind of information transformation that goes on inside your head. As the models become more refined, the level of detail represented by a box becomes finer. A box that represents a relatively fine level of detail is often called a stage of information processing (Sternberg, 1975; Taylor, 1976) or an isolable subsystem (Posner, 1978). The precise definition of a stage is mathematically sophisticated (Townsend, 1974) but we will not be far off if we think of a stage as corresponding to a single transformation of information. In general, the output of a stage will not match its input. For example, one common model of memory assumes that printed words received through the eyes get recoded into a format that is related to how the words sound when read aloud. This transformation occurs even though people were not asked to pronounce the words. So a visual input has been transformed into an auditory (i.e., acoustic or phonological) output. This kind of transformation is common in machines. A computer transforms punched holes in cards into electrical impulses. A telephone transforms electrical signals into air vibrations. So it is not surprising that the human information processor is capable of these kinds of internal information transformations.

Different arrangements of stages are required to model the flexibility of the human information processor. The simplest arrangement occurs when several stages are linked in a straight line (or in cascade) with the output of one next becoming the input of the succeeding stage. This is called serial processing because no stage can perform its own transformation of information until it receives the output of the preceding stage in the chain. This, of course, will not happen until that stage has received information from its preceding stage. So the stages are like a row of dominoes. Tipping the first domino over starts a reaction but this is propogated slowly down the line of dominoes. Similarly, serial processing models require each stage to wait its turn before producing an output.

If a stage need not wait for other stages to finish, the arrangement is called parallel processing. In parallel processing several stages can access the same output simultaneously. Each parallel stage can do its own thing without having to wait for other parallel stages to complete their processing. An arrangement with both serial and parallel components is called hybrid processing. Hybrid processors are often more powerful than serial or parallel processors but this extra power is gained by making the model more difficult to understand and analyze. Since many people find serial models easier to understand, most information-processing models are serial. But my crystal ball predicts that parallel and hybrid models will become dominant soon.

Although we now have an excellent scheme for classifying the structure of a model into three categories--serial, parallel, and hybrid-- structure alone cannot determine the predictions a model will generate. We must also know the "price" each stage demands for performing its transformation of information. This is called resource allocation or capacity. Capacity is a hypothetical construct that controls how efficiently a stage operates. In some models, it is assumed that each stage has adequate capacity to do its own thing, regardless of how many other stages are operating and how complex these operations might be (Sternberg, 1969). Other models assume that capacity is limited so that stages must compete for available processing resources (Kantowitz & Knight, 1976). In these models, a stage cannot always operate as efficiently as if it were the only stage in the system. Other stages may divert the necessary capacity. By cleverly selecting assumptions about capacity it is possible to make serial systems mimic parallel systems and vice versa (Townsend, 1974). Thus, in order to generate predictions for a model, we must specify both the structure of the model and its capacity assumptions. The best models of human information processing specify (1) the number and configuration of internal processing stages, (2) the capacity requirements of individual stages, and (3) total availability of capacity and rules that govern distribution of capacity to individual stages.

A variety of attention models, with varying assumptions about capacity allocation, are currently viable. Space limitations here prevent a review of these models but see Kantowitz (1984;1974) and Lane (1982) for critical evaluations. One important dimension contrasts single- versus multiple-resource models. Since the traditional single resource model is the serial single-channel model proposed by Broadbent (1958) and later modified (1971) it does not fare well in competition with newer multiple-resource models proposed by Navon and Gopher (1979) and Wickens (1980). The fundamental problem with multiple-resource models is that they explain too much, that is, were they to be formulated in a mathematically rigorous fashion, the number of free parameters would be quite large. This is explained in an article in press in the Journal of Mathematical Psychology that evaluates this class of model (Kantowitz, 1984). Furthermore, serious scaling problems arise when these models have been used to explain the timesharing of two independent tasks. The typical performance operating characteristic function (Norman and Bobrow, 1975) has been calculated by transforming both task dependent measures into z-scores. This places severe constraints on the underlying performance-resource functions which, of course cannot be directly observed, and in general is not a meaningful transformation (Kantowitz, 1984). Thus, support for multiple-resource models based upon timesharing paradigms where z-score transformations have been used must be interpreted with considerable caution. Indeed, some of the early enthusiasm for multiple-resource models is being tempered and both Navon (personal communication) and Klapp and Wickens (personal communication) have reduced some original claims and now are aware of some of the limits of multiple resources.

Thus, we suspect that hybrid models will play an increasingly important role as theories of attention develop, although to be candid it should be noted that this enthusiasm stems from one of the earliest hybrid models of attention and workload (Kantowitz and Knight, 1976). This model is depicted in Figure 1 and forms the theoretical base for this proposed research. There are two ways in which the human information processor can be overloaded. First, successive stimuli and/or responses can be temporally placed in such close juxtaposition that the human cannot transmit a high enough rate of information to keep up with the task. A prime example of this occurs in the psychological refractory period paradigm, to be discussed at length later in this proposal. Second, independent tasks may be timeshared with one or both tasks being increased in difficulty until the human can no longer cope. While it is customary to increase the workload of the primary task, it should be noted that a theoretical evaluation of any timesharing experiment demands simultaneous manipulation of both primary- and secondary-task difficulty. The reasons for this statement are too complex to be covered here but have already been expressed in some detail by Kantowitz and Knight (1976). So although timesharing studies with only one level of secondary task difficulty or complexity can be useful in solving applied problems, insofar as basic research and theory are concerned only those relatively few studies that simultaneously manipulate both tasks can refine our understanding.

The hybrid model of Figure 1 accounts for results of both kinds of overloading: psychological refractory period effects and timesharing. Its structure allows parallel processing of incoming perceptual information but demands serial processing of response selection and execution stages. A single limited-capacity source drives all stages. (There are some restrictions on how the static capacity allocator divides capacity among the parallel stages, but this aspect of the model is not directly relevant to the proposed research in Phase I. It will be of greater interest during Phase II.) The model states that although attentional limitations can occur in perceptual processing (if there are too many parallel stages or the static capacity allocator is not set optimally), by and large the crucial bottleneck in human information processing occurs in response selection, provided of course that stimuli are not degraded. It is obvious that poor stimulus quality (e.g., data-limited process) will impair performance, but this is more a limitation of the environment, rather than a basic limit on human processing capabilities, (see Kantowitz and Knight, 1976b for an explanation of experimenter-limited processes), and so is more of applied interest than theoretical importance. Hence, the proposed research uses tasks that allow investigation of the response selection process by, for example, using stimulus-response sets that provide at least one bit of information.

Although the following major section describes the psychophysiology of attention, it is appropriate to discuss the relationship between behavioral models of attention and psychophysiological measures now in the context of Figure 1. We believe that the most careful and elegant psychophysiological measures will not improve our understanding of workload unless the behavioral tasks are appropriately selected within some viable model of attention, (not necessarily the hybrid model although we prefer it as being more parsimonious than multiple-resource models). Eventually, refined psychophysiological models will tread where behavioral models cannot go. But now it is crucial to restrict taking biocybernetic measures to situations where the workload can also be estimated from the behavior. This is the essence of converging operations. Some researchers have gone beyond this stricture by relying solely upon neural measures. For example, Gill and Wickens (1982) used P300 ERP waveforms while subjects controlled a second order system. An auditory secondary counting task was used to elicit ERPs. No differences in ERPs were obtained among different primary-task categories. The authors concluded that operator workload remained constant. This conclusion, while not necessarily incorrect, was premature. It relied only upon the psychophysiological data since the experiment did not have the necessary behavioral conditions to justify such a conclusion. Even worse, the behavioral data on the secondary counting task were not reported! Hubris begets nemesis. A minor design change in the experiment would have allowed counting estimates to be scored as a function of the same category states used with the ERP data. If the conclusion is correct, one would expect no behavioral differences in secondary task performance either. This would have provided a converging operation that would have greatly increased the credibility of the conclusion which involves accepting a null hypothesis. In the clear view of hindsight it is easy to see that the authors allowed their enthusiasm for ERP data to blind them to the need of obtaining converging behavioral data. The proposed research always contains the necessary experimental and control conditions required to estimate workload from behavior. Psychophysiological measures are intended to provide converging operations. Using only psychophysiological measures is premature and suffers from the same logical flaw as attempts to measure workload by using only subjective estimates and rating scales.

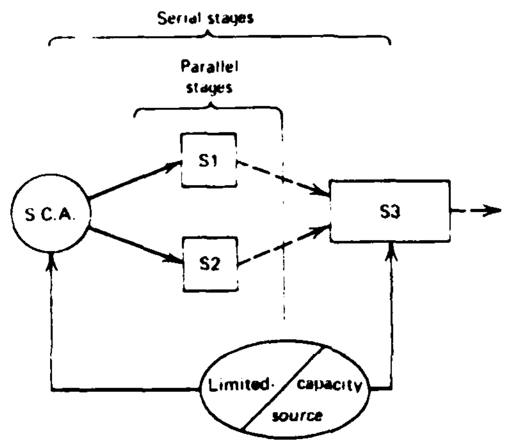


Figure 1. A hybrid processing model with serial and parallel stages. The parallel stages represent early or perceptual information processing. They are controlled by a static capacity allocator (S.C.A.) that divides capacity between them. (From Kantowitz & Knight, 1976.)

Psychological Refractory Period

Overloading the human by increasing the rate of incoming stimuli requires a minimum of two successive stimuli. While a real-world environment consisting of only two stimuli would be rare, this is the optimal number of stimuli for laboratory study. Any additional stimuli only increase complexity without expanding the potential for gaining knowledge and understanding. In the psychological refractory period task, two stimuli are presented in close temporal succession, usually less than 500 milliseconds apart. The time between the two stimuli is called the inter-stimulus interval (ISI). An ISI =0 means that the two stimuli occur at the same time.

The earliest study of the psychological refractory period (Telford, 1931) found that reaction time to the second signal was considerably delayed. It was as if the brain turned off after receiving the first signal. Thus, the phenomenon was named the psychological refractory period by analogy to the refractory period of a single neuron which will not respond to a second input when it is stimulated by signals that arrive close together. While this explanation is no longer believed (see Kantowtz, 1974a), the descriptive name has remained.

As ISI is decreased, the human is more and more overloaded. This can be measured by recording reaction time to the two stimuli. When the two stimuli are far apart --at large ISIs--reaction time is fast. As ISI gets smaller, reaction time increases. Reaction time is often interpreted as an index of load or capacity (but see Broadbent, 1965 and Kantowitz, 1984 for possible dangers associated with this line of reasoning). Thus, at short ISIs the human is badly overloaded. The limited channel model explained the delay in reaction time to the second stimulus as being due to processing of the first stimulus. Until the first stimulus clears the channel, the second stimulus cannot be processed with normal efficiency. The overlap between first and second stimuli is greatest at shorter ISIs, so reaction time to the second stimulus is most delayed when the two stimuli occur close together.

However, later research discovered that there is also a delay to reaction time for the first stimulus (Herman & Kantowitz, 1970). This finding cannot easily be explained by the limited capacity channel model without making complicated assumptions about interruption of processing and push-down stacks. Since the channel is empty at the time the first stimulus occurs, there should be no reaction time delay. But data show that reaction time to the first stimulus also decreases as ISI increases, although first reaction times asymptote before second reaction times (Kantowitz, 1974b). Newer models are superior to the limited capacity channel model because they can explain reaction times to both first and second stimuli, whereas the limited channel model can only handle reaction times to second stimuli in the psychological refractory period task. A review of models and results in the psychological refractory period and related paradigms can be found in Kantowitz (1974a).

The hybrid model in Figure 1 explains delays in reaction time to both first and second stimuli as due to response conflict localized in Stage 3. While the human can correctly perceive S1 and S2, the time needed to organize and select appropriate actions causes RT delays, increasing error rates, or both. The amount of overload can also be manipulated by varying the number of stimulus-response alternatives. With only a single response key (e.g., zero response uncertainty) there is no RT delay. Increasing response uncertainty yields increasing RT delay.

Because the psychological refractory period paradigm produces so reliable an effect, and because its theoretical interpretation is so well understood, it is an ideal test bed for phase I. The timesharing paradigm is more complex and fraught with an assortment of technical (and theoretical) perils (Kantowitz, 1984) so that timesharing studies will be deferred to phase II. Thus, the goal of phase I research is to take psychophysiological measures in a psychological refractory period paradigm to provide converging operations within a theoretical framework that has already been validated behaviorally, but not psychophysiologically.

Psychophysiology of Mental Workload

Research on the psychophysiology of mental workload has proceeded in two relatively independent directions, chiefly characterized by the emphasis upon central or autonomic measures. Electroencephalography (EEG) correlates of workload have focused upon P300 as a measure of central processing (Israel et al., 1980) and spatial and temporal dynamic patterns of evoked potentials during mental work (Gevins et al., 1979, 1981, 1983). These techniques require steady-state workload conditions for averaging. EEG work oriented toward field applications has emphasized laboratory analysis of single-trial evoked potentials (Aunon et al., 1982), and single-trial evoked potentials in a flight simulator (Wilson et al., 1982) with more limited success.

A parallel literature on cardiovascular correlates of workload has witnessed a proliferation of measures of heart rate (HR) variability. New developments in the application of time series analysis (particularly spectral analysis) to describe HR variability in terms of frequency components allows a more focused approach to measuring workload that appears to be readily applicable to both field and laboratory environments.

Because central and autonomic approaches to the psychophysiology of workload have proceeded in different laboratories, less is known about their comparative advantages and disadvantages. Research is needed in which evoked potential and HR measures are recorded together in a standardized workload paradigm that emphasizes response load. In addition, technological advances in portable measurement of HR allow immediate application of laboratory techniques to the field environment where evoked potentials are more difficult to measure.

P300

P300 is a positive wave in the average evoked potential of the EEG that typically occurs approximately 300 msec following the evoking stimulus. Interest in P300 stems largely from its relative independence from physical characteristics of the evoking stimulus, combined with its correlation with a range of variables related to cognitive factors. In an excellent review of the P300 literature, Pritchard (1981) evaluated different theoretical interpretations of P300, ranging from early information theory analyses in terms of uncertainty resolution (e.g. Sutton et al., 1967), Donchin et al.'s (1973) proposal that P300 reflects a general purpose cognitive process, to Posner's (1978) view of P300 as reflecting a central processor directly related to conscious awareness that is capacity limited. Pritchard argued that P300 might be best understood in terms of a neurocognitive model in which P300 reflects the updating of neuronal models of future events.

Controversy over theoretical interpretations of P300 are likely to continue as further research on P300 develops. However, some basic conclusions can be reached at the present time that have important implications for the proposed research. First, P300 is sensitive to perceptual characterstics of the evoking stimulus primarily to the extent that it places demands on limited capacity perceptual resources. For example, Magliero et al. (1982) and McCarthy and Donchin (1981) found that P300 was sensitive to perceptual noise, and a series of dual-task studies (Towle et al., 1980; Israel et al., 1980) have provided additional evidence. In fact, the classic workload study by Israel et al. (1980) may reflect perceptual rather than cognitive overload. In this analog study of air traffic control, subjects monitored a display of moving objects on a screen, with instructions to detect course changes and flashes of different objects. The amplitude of the P300 elicited by flash and course-change stimuli was negatively related to workload. Instructions to simply count rare events produced a large P300, while monitoring four and eight display elements yielded progressively smaller P300's. Therefore, P300 appears sensitive to perceptual overload when response load is held constant.

Second, P300 is sensitive to a host of central cognitive processes such as orienting and stimulus evaluation in terms of probability, salience, etc. Pritchard's (1981) interpretation of these relationships in terms of updating neuronal models of future events suggests that the Phase I paradigm may be one to which P300 is sensitive. This is because the warning tone that serves as the evoking stimulus for P300 carries information concerning the future response load.

However, a final conclusion is warranted that may counteract this. On the basis of recent evidence, researchers (Pritchard, 1981; Wickens et al., submitted) have concluded that P300 is not sensitive to response selection factors. Magliero et al. (1982) manipulated perceptual noise and response requirements while measuring P300 latency and reaction time. While reaction time was sensitive to both perceptual noise and response requirements, P300 latency was related only to perceptual noise. Two studies (Duncan-Johnson and Kopell, 1980; Warren and Marsh, 1979) using the Stroop effect have found no relationship between P300 and response competition. In addition, P300 latency may or may not be related to reaction time depending upon stimulus evaluation time rather than response selection and execution time (Donchin, 1979; Prichard, 1981).

The implication of this evidence is that P300 may not be sensitive to the response load manipulation in the Phase I paradigm. However, to the extent that P300 reflects a neural updating process to future events (Pritchard, 1981), then it may be sensitive to the predictive information carried in the warning tone even though it relates to response load. Furthermore, P300 may allow separation of perceptual versus response effects in the psychological refractory period paradigm.

HR variability

Heart rate (HR) is extremely variable over time, and this variability is inversely related to mental workload (Kalsbeek et al., 1963, 1965, 1971). Since this early research, procedures for quantifying HR variability have proliferated (Firth, 1973), producing much confusion in the area. However, the increasing sophistication and availability of time series analysis procedures in the frequency domain provides a focal point for research on HR variability. The values of this approach are (a) the HR frequency components are interpretable in terms of known physiological systems, (b) HR variability can be broken down into different components that discriminate between endogenous physiological rhythms and exogenous rhythms produced by the workload task, (c) frequency components can be easily quantified in terms of variability or coherency indices that are reliable and valid.

The best understood frequency component in the HR spectrum is associated with respiratory sinus arrhythmia. This component represents rhythmic variation in HR that is coherent with tidal respiration. Porges et al. (1980, 1981) has developed frequency domain procedures to quantify respiratory sinus arrhythmia in terms of HR variability at the dominant respiratory frequency (approximately 0.25 to 0.35 Hz). The raw HR series must first be transformed into a discrete series with a constant sampling rate that is at least twice the frequency of the highest frequency component of interest, and the resulting series must be differenced at least once to remove linear trend. Using spectral analysis, $\hat{V}$ is calculated as the accumulated spectral power in the HR series in the respiratory sinus arrhythmia frequency band spectral analysis, Cw is the weighted coherence.

Porges' work on respiratory sinus arrhythmia represents a model for quantifying HR variability components in a workload paradigm. These components represent (i) respiratory sinus arrhythmia, (ii) slower endogenous rhythms related to renal, blood pressure, and temperature regulation (Akselrod et al., 1981), and (iii) exogenous frequency components directly attributable to the temporal characteristics of the workload task.

The exogenous components must be considered carefully in the choice of the workload task. The task may be structured so that it produces rhythms at a different dominant frequency from the known endogenous rhythms by choosing a constant stimulus presentation or response rate that does not excite or obscure these rhythms. This approach allows calculation of variability due to phasic responses to the task. An alternative approach is to use a randomly variable presentation rate so that no task-induced rhythm is found in the HR spectrum. Variability due to task is then represented by additional noise in the HR spectrum. The addition of a secondary task is a further complication because it adds a second exogenous component attributable to the temporal characteristics of the secondary task.

<u>Advantages and Disadvatages</u>

The primary advantage of central measures of workload, such as P300, is that they tap perceptual cognitive functions. For models of workload that emphasize capacity limitations in early processing stages, P300 has many advantages. However, the hybrid model advanced above places greater emphasis upon capacity limitations associated with response load, and P300 may or may not be sensitive to this stage of processing.

The primary disadvantage of central measures is that they are closely tied to the laboratory environment, and major technological advances are needed before they can be applied easily in a field environment. In addition, P300 requires substantial averaging, which often is not feasible in the field.

Peripheral measures, particlarly HR variability, reflect system integration and control. The cardiovascular system is a complex, controlled system that must be maintained within physiological limits. HR rhythms are the oscillatory signature of centrol control. The primary advantage of HR variability measures of workload is that they reflect system disturbances that probably include response load. Research is needed in which the sensitivity of HR variability to response load is examined systematically. This need is particlarly apparent in light of the model of workload advanced above.

A second advantage of HR variability measures is that they can be obtained easily in the field. Devices such as the Vitalog allow portable, unobtrusive recording in a variety of field environments.

HR variability measures also have important limitations. First, they require steady-state workload conditions, and are not applicable to brief, single-trial tasks. It is possible that the evoked HR response is both sensitive to workload and sufficiently reliable for a single-trial paradigm, and this will be investigated. Second, HR variability is linearly related to mean HR, and variability measures must be corrected for this relationship. However, to the extent that mean HR is itself sensitive to workload, then correcting for mean HR may reduce the sensitivity of the variability measure. This problem will be handled empirically to determine the most sensitive HR measure. Finally, HR measures (particularly mean HR) are sensitive to affective responses associated with work overload.

EXPERIMENT 1

Method

Behavioral Variables

In the psychological refractory period paradigm, three stimuli are presented in sequence to form a single trial. First a warning signal (W) alerts the subject. We used an auditory warning signal 500 msec in duration with an intensity of 70 dB SPL. A variant of the partial advance information technique (see Kantowitz & Sanders, 1972) was used in both Experiments 1 and 2 so that the warning signal could convey partial event information. A high-frequency W (2.5 KHz) denoted a four-choice trial and a low-frequency W (880 Hz) denoted a two-choice trial, where number of choices refers to the information in S1, the first stimulus demanding an overt response.

A random foreperiod (W offset to S1 onset) with a mean of 2.0 sec was created by sampling foreperiods of 1.5, 2.0, and 2.5 sec equiprobably. The stimulus array was a set of four high-intensity LEDs arranged in a horizontal line slightly below the subject's eyelevel at a distance of 164 cm. The LEDs were placed close together, spanning a distance of 4 cm, so that the entire display was foveal. On two-choice trials, only the inner two LEDs were illuminated. Thus, once S1 had appeared, S2 was certain, e.g., the remaining inner LED. S2 appeared either 60, 240 msec after S1 onset or not at all in the single-stimulation control condition. The inter-stimulus interval (ISI) between S1 and S2 was constant for each 33-trial block. The first trial of each block was discarded as practice. In Experiment 1 number of choices (2 or 4) was constant within a block of trials.

Responses were made on four piano-like keys operated by the second and third fingers of each hand. A correct response extinguished the appropriate LED. The intertrial interval (W onset to W onset) was 6 secs.

A Cromemco CS1 microcomputer equipped with a Mountain Hardware S-100 clock controlled stimulus presentation and recorded reaction times to the nearest millisec. The computer also sent a signal via a parallel port to another Cromemco Z-2 system that recorded biocybernetic data. Signals were transmitted on each trial to mark onset of W and onset of S1.

All 3! orders of ISI were used with 2 subjects randomly assigned to each order. Subjects were 12 Purdue University male students who were paid $5 per hour for participation. Experiment 1 consisted of 8 blocks of trials: a single-stimulation practice block (either 2- or 4-choice) followed by 3 blocks permuting ISIs of 60 msec, 240 msec and single-stimulation control. These 4 blocks were then repeated for the remaining choices (either 4- or 2-choice). Thus, half of the subjects received 4 blocks of 2-choice trials followed by 4 blocks of 4-choice trials, while the other 6 subjects received the opposite order. Note that since number of choices was constant for a block of trials, the partial advance information conveyed by the warning signal was completely redundant. (However, two different warning tone frequencies were used to facilitate planned comparisons with Experiment 2 where partial advance information was useful.)

Subjects were instructed to stress speed, rather than accuracy of responding, and were told to respond to each stimulus as soon as it appeared, i.e., to avoid grouping. A short rest break occurred after each block of trials, while data was written to floppy diskette.

Autonomic Measures

Cardiovascular activity was recorded on a Grass Model 79 Polygraph with outputs to the A-D converter of the Cromemco Z-2. Activity was recorded as a series of inter-beat intervals (IBI), a measure that is the reciprocal of heart rate, and that is better suited to spectral analysis. Bard prejelled disposable EKG electrodes (#160100) in bipolar configuration on the sides of the chest were used to obtain IBI. Respiration data were obtained from a mercury-in-rubber strain gauge attached around the chest and sampled at 2 Hz.

Spectral Analysis.--Spectral analysis of cardiovascular activity was carried out using procedures modeled after Porges et al. (1980, 1982) using time series analysis software written by Williams and Gottman (1982). The IBI series corresponding to each heart beat was first edited to remove any artifacts by interpolating missing IBI values according to an algorithm developed by Porges. The series was then transformed into a discrete series with a constant sampling rate of 1 Hz. Each 1 sec point consisted of the sum of the IBI values lying in the interval surrounding that sampling point multiplied by the proportion of the interval that each occupied. The series was then differenced to remove linear trend.

Spectral analysis was performed for both IBI and respiration data. This analysis produces a series of variability indices representing peaks in the heart-rate spectrum. The variability index, $\hat{V}$, is calculated by accumulating spectral power over a fixed bandwidth for each frequency component (Porges, 1981).

Each $\hat{V}$ is expected to correspond to known frequency components in the human heart-rate spectrum. The highest frequency component should correspond to respiratory sinus arrhythmia (RSA), confirmed by examination of the respiratory spectrum. This component should peak at 0.25 to 0.33 Hz, corresponding to respiration rates of 15 to 20 breathes per min. An additional peak at approximately 0.10 Hz is expected, corresponding to endogenous rhythms associated with blood pressure (BP) regulation.

Prior to starting the behavioral blocks of the experiment, IBI was recorded for a 5 min period to establish a resting baseline for each subject. Another 5 min resting period was recorded after the fourth block, midway through the experiment.

RESULTS

Behavioral Data

Figure 2 shows mean reaction time as a function of number of choices and ISI. Results were entirely as expected. For RT_2 4-choice RT substantially exceeded 2-choice RT, $F(1,6) = 134$, $p<.001$. RT_2 was greater at the 60 msec ISI, $F(1,6) = 216$, $p<.001$. For 4-choice conditions RT_2 was significantly elevated relative to the single-stimulation control conditions, ts$(12) > 5.30$, $p<.001$. However, for 2-choice conditions, RT_2 at the 240 msec ISI did not differ from the single-stimulation control condition, $t(12) < 1.0$. This was as expected since, in the 2-choice condition, S2 was certain once S1 occurred and 240 msec is sufficient time to complete a substantial fraction of S1-R1 processing. At the 60 msec ISI, RT_2 was reliably greater than the single-stimulation control condition, $t(12) = 4.68$, $p<.001$ because 60 msec is not enough time to reduce S2 uncertainty.

For RT_1 4-choice RT exceeded 2-choice RT, $F(1,6) = 155$, $p<.001$. Effects of ISI were not significant, $F(1,6) = 3.56$, $p>.05$, as is usually the case for RT_1. As expected, both 2-choice, ts$(12)>4.09$, $p<.01$, and 4-choice, ts$(12)>10.8$, $p<.001$, conditions were significantly elevated relative to their single-stimulation control conditions.

Figure 3 shows response accuracy as a function of number of choices and ISI. For R2 accuracy only the effect of Choices was significant, $F(1,6) = 7.98$, $p < .05$. Thus RT_2 results are not due to a speed-accuracy trade-off. R2 accuracy was highest for the single-stimulation control condition, $F(2,12) = 7.04$, $p < .01$.

For R1 accuracy no effects reached the .05 level of significance. However, there was a marginal effect of ISI, $F(1,6) = 5.00$, $p < .07$, that might be expected under the present accuracy instructions (Knight & Kantowitz, 1974). R1 accuracy was highest for the single-stimulation control condition, $F(2,12) = 4.37$, $p < .05$.

For both R1 and R2 control conditions were faster and more accurate. Hence differences between single- and double-stimulation conditions cannot be attributed to speed-accuracy trade-off.

Autonomic Measures

Mean IBI and IBI standard deviations were calculated on successive heart beats from the onset of the warning tone of each trial until the warning tone of the next trial. The spectral

Figure 2. Mean reaction times for first and second responses. SS = single-stimulation control condition. ISI = S1-S2 inter-stimulus interval.

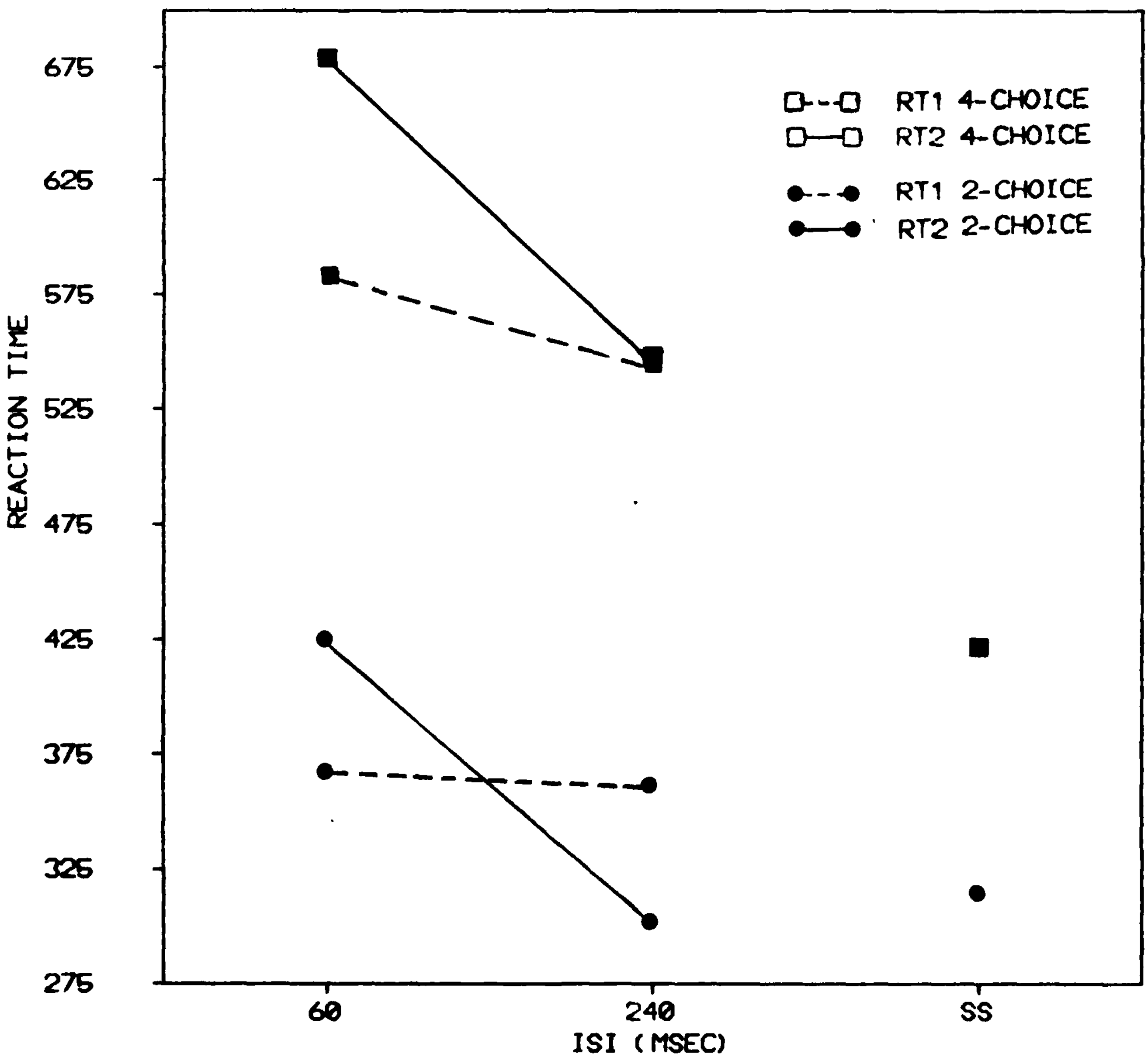
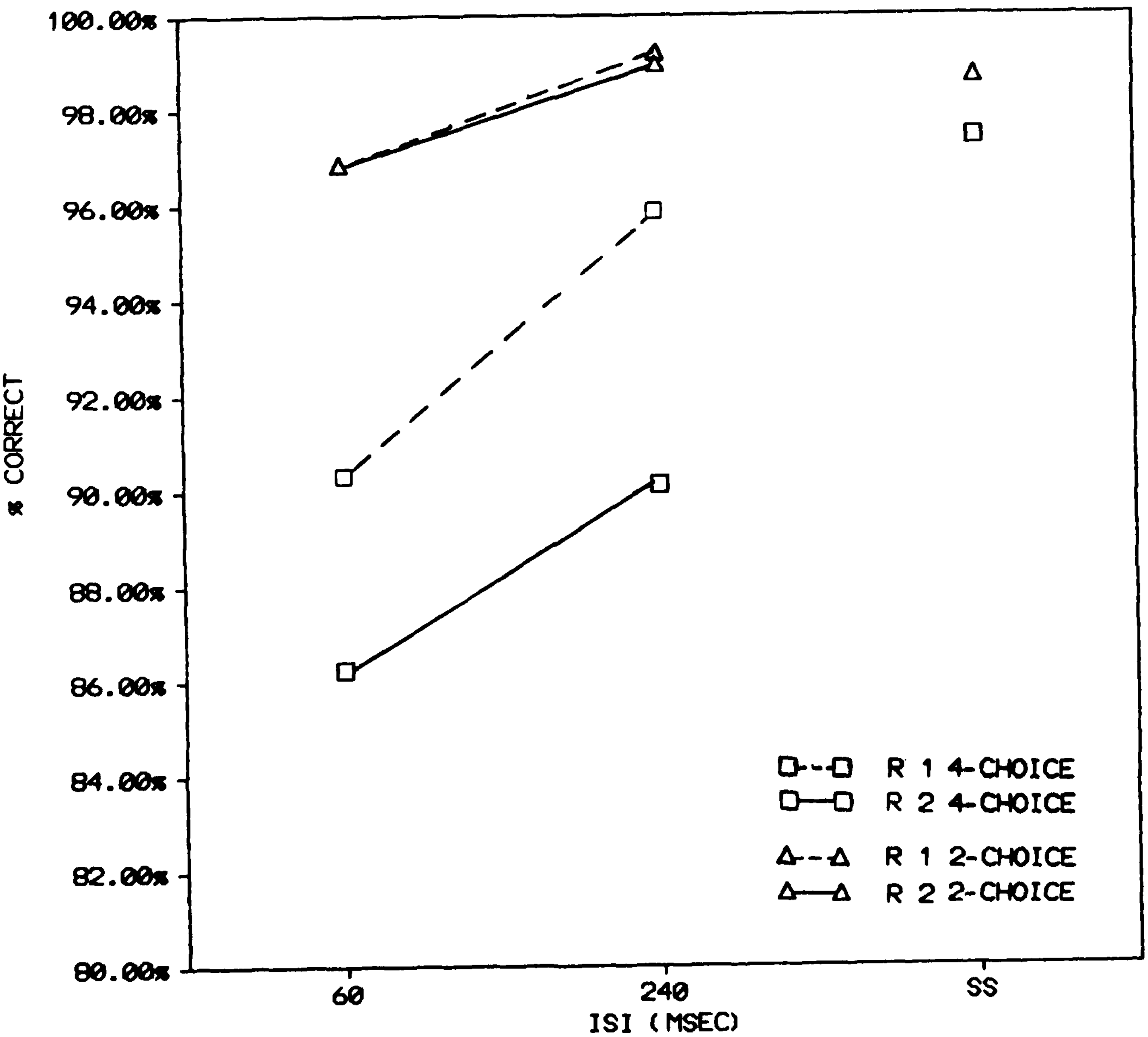


Figure 3. Mean accuracy for first and second responses.



estimates, $\hat{V}_{RSA}$ and $\hat{V}_{BP}$ were calculated on IBI data from each block. Successive IBIs were first transformed into sec-by-sec IBI trains of 280 IBIs, then differenced to remove linear trend, and then submitted to spectral analysis with 140 lags.

The RSA peak was located in the resulting spectra by inspecting the corresponding spectral peak for respiration. $\hat{V}_{RSA}$ was calculated as the sum of spectral powers in a 10 lag bandwidth around the peak power, located by reference to the dominant respiratory frequency. $\hat{V}_{BP}$ was located as the largest peak in the 8 to 12 sec interval range, and $\hat{V}_{BP}$ was calculated as the sum of spectral powers in a 10 lag bandwidth about this peak. Summation of spectral powers has been justified because adjacent estimates are theoretically independent (Porges et al., 1981). The spectral estimates, $\hat{V}_{RSA}$ and $\hat{V}_{BP}$, were submitted to log transformations prior to the statistical analyses to reduce the great variation present in the raw estimates.

All IBI data (mean IBI, IBI standard deviation, and spectral analyses) were statistically analyzed using a repeated measures MANOVA instead of the ANOVA used for behavioral measures. Biocybernetic data, where carry-over effects are likely, fit the underlying MANOVA model better than they satisfy the ANOVA assumptions (Tabachnick & Fidell, 1982, p. 228).

Figure 4 shows mean IBI as a function of Choice and ISI. Effects of Choice (2 vs 4) were significant, $F(1,11) = 12.8$, $p <$ blocks of trials. Effects of ISI (60 msec, 240 msec, single-stimulation), $F(2,10) < 1.0$, and its interaction with Choice, $F(2,10) = 2.12$, $p > .05$, were not significant,

Figure 5 shows IBI standard deviation as a function of Choice and ISI. The pattern of results was the same as for mean IBI. Only effects of Choice were significant, $F(1,11) = 11.9$, $p < .006$.

Figures 6 and 7 show spectral data as a function of Choice and ISI. Again the same pattern was obtained. Effects of Choice were significant for log $\hat{V}_{RSA}$, $F(1,10) = 5.17$, $p < .05$, and effects of ISI and its interaction were not. For log $\hat{V}_{BP}$ no effects were significant, although effects of Choice came closest, $F(1,10) = 3.52$, $p < .09$.

Figure 4. Mean inter-beat interval (IBI) as a function of ISI.
B = first baseline resting period prior to starting behavioral manipulations.

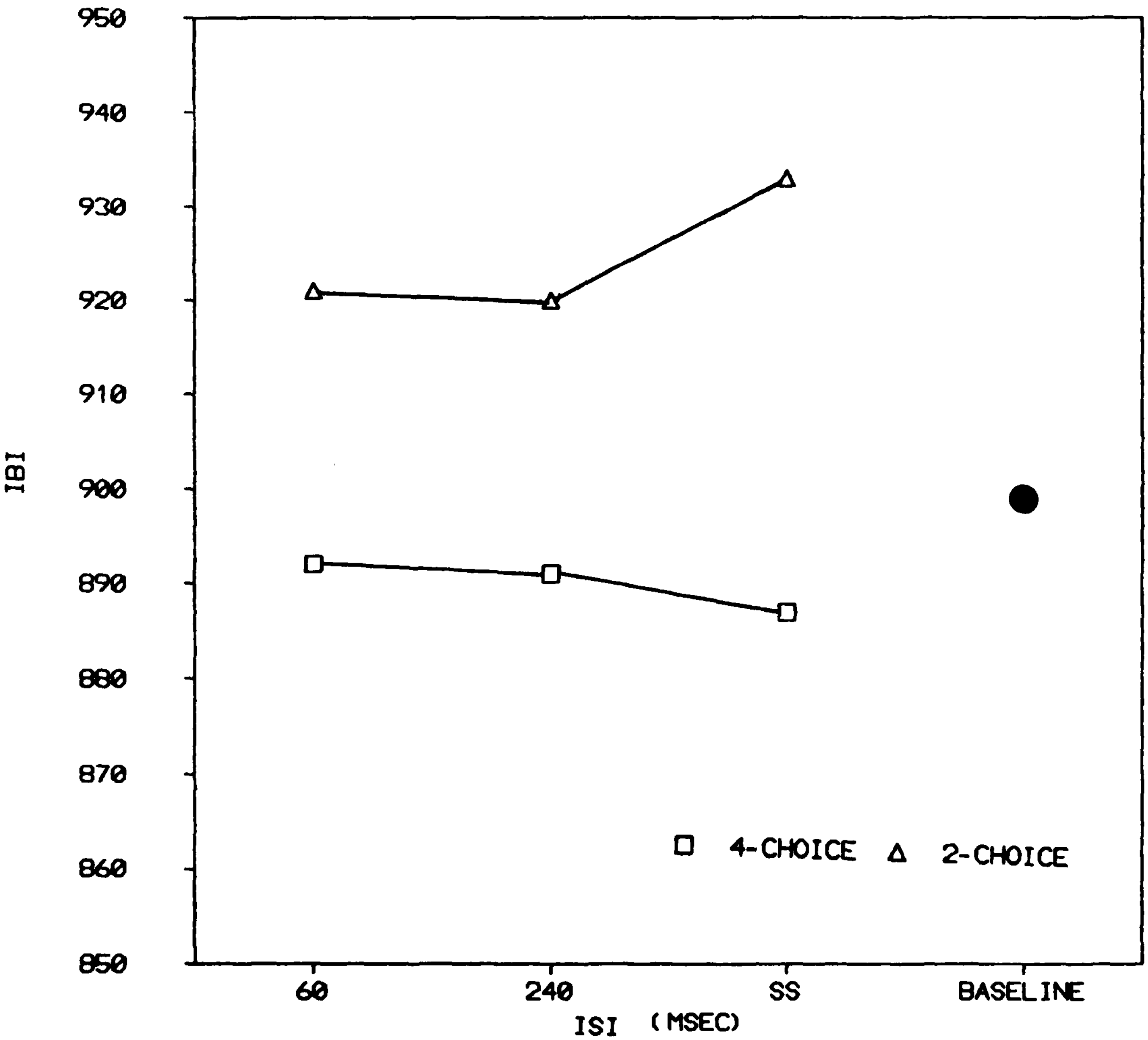


Figure 5. Mean inter-beat interval (IBI) standard deviation as a function of ISI.

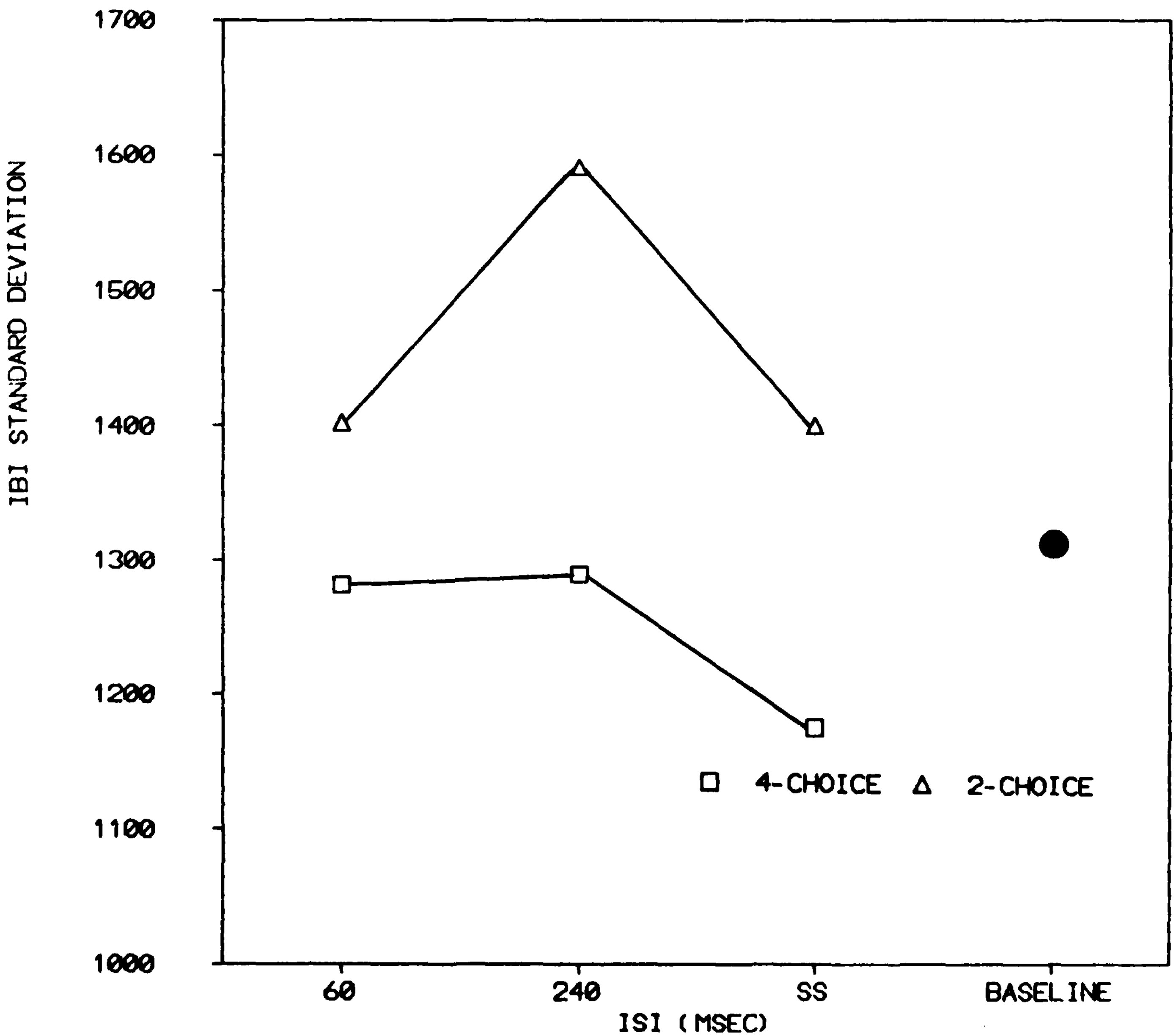


Figure 6. Log $\hat{V}_{RSA}$ as a function of ISI.

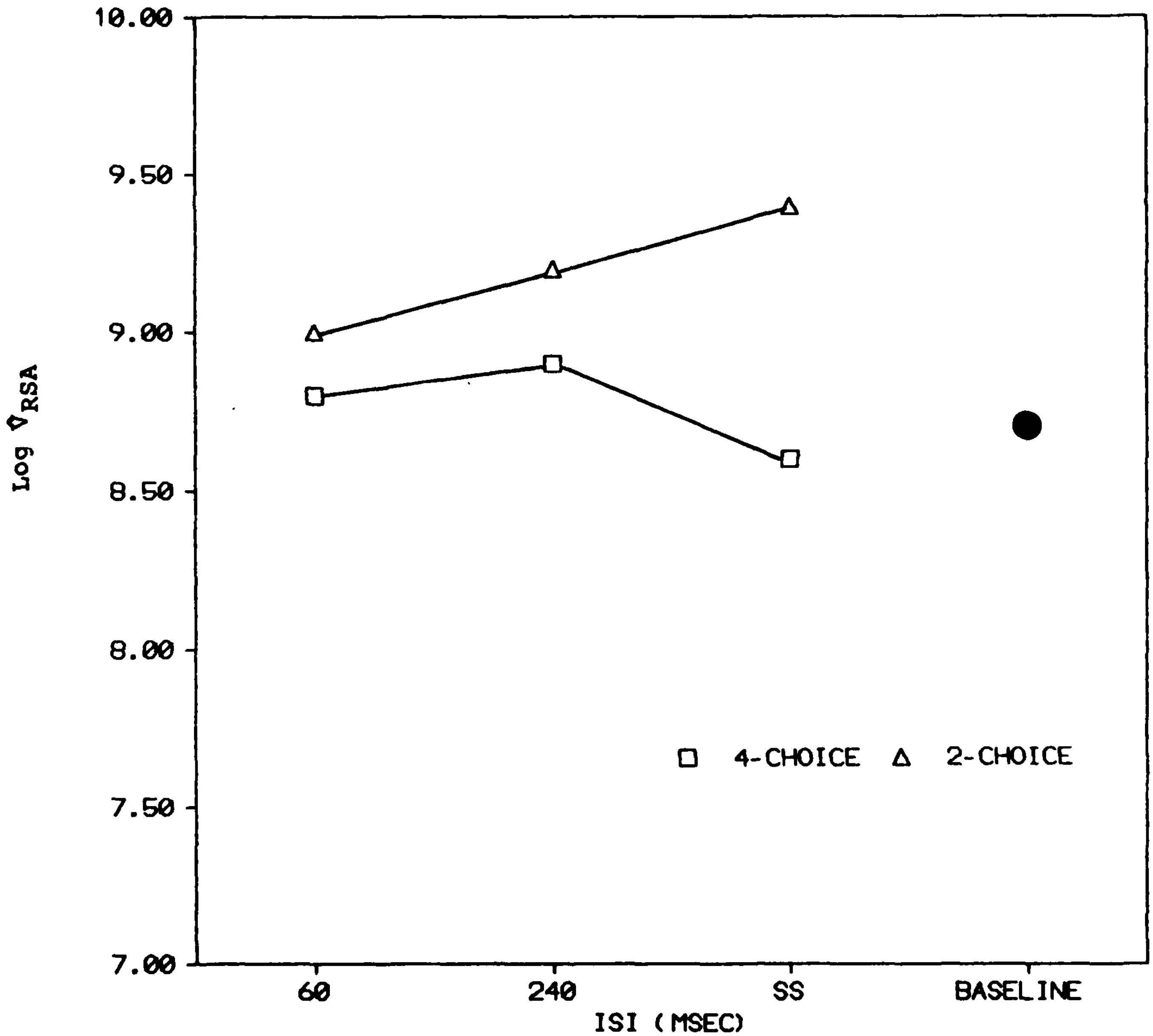
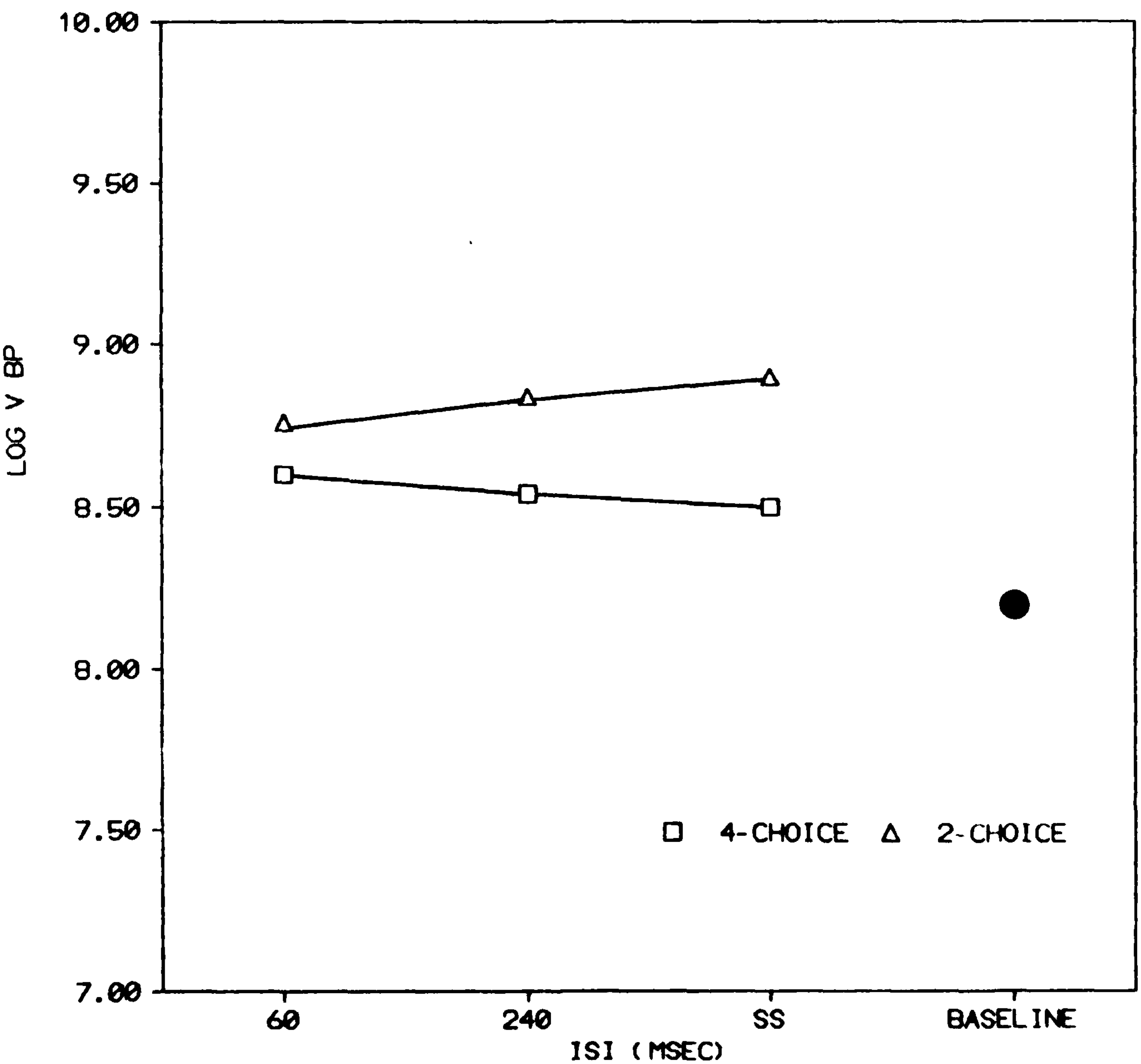


Figure 7. Log $\hat{V}_{BP}$ as a function of ISI.



EXPERIMENT 2

Method

Behavioral Variables

Experiment 2 was virtually identical to Experiment 1 except that (a) there were two sessions of 4 blocks each, and (b) 2- and 4-choice trials were randomized equiprobably within each block. Only data from session 2 were scored. Twelve male Purdue University students who had not participated in Experiment 1 were paid subjects.

Biocybernetic Variables

In Experiment 2 inter-beat interval (IBI) was recorded as in the previous experiment, except that to allow time for attaching and removing scalp electrodes in addition to EKG electrodes no prior baseline condition was established.

EEG and electro-oculogram were recorded using 3 Grass 7P122 DC amplifiers, bandpass filtered from 0.1 to 36 Hz, with outputs routed to the A-D convertors on a Cromemco Z-2 microcomputer. Cz and Pz, referred to linked ears with grounded forehead, were recorded using Beckman silver/silver chloride electrodes and Med-Tek synapse conductive electrode cream (SYN 1505). Vertical eye movements were recorded with Beckman electrodes around the right eye. EEG was recorded for only 6 subjects corresponding to one replication of the 3! orders of ISI.

EEG was sampled at 100 Hz for one sec following S1 onset; limitations of the 64K memory of the Z-2 prevented recording at W onset. Electro-oculogram was sampled at 10 Hz for one sec following S1 onset. Trials that are contaminated by a vertical eye movement were discarded to prevent eyeblink artifact.

RESULTS

Behavioral Data

Figure 8 shows mean reaction time as a function of number of choices and ISI. Again results were as expected. For RT_2 effects of number of choices, $F(1,6) = 127$, and ISI, $F(1,6) = 31.1$, $p<.001$, were significant. Double-stimulation RT_2 was elevated relative to appropriate single-stimulation control conditions, $\underline{t}s(12) > 4.77$, $p<.001$ only for the 4-choice condition as was the case for Experiment 1. For the 2-choice condition the 60 msec ISI was elevated relative to the single-stimulation control condition, $\underline{t}(12) = 4.48$, $p<.001$, while the 240 msec condition was not, $\underline{t}(12) = 1.58$, $p>.05$. This replicates the results of Experiment 1.

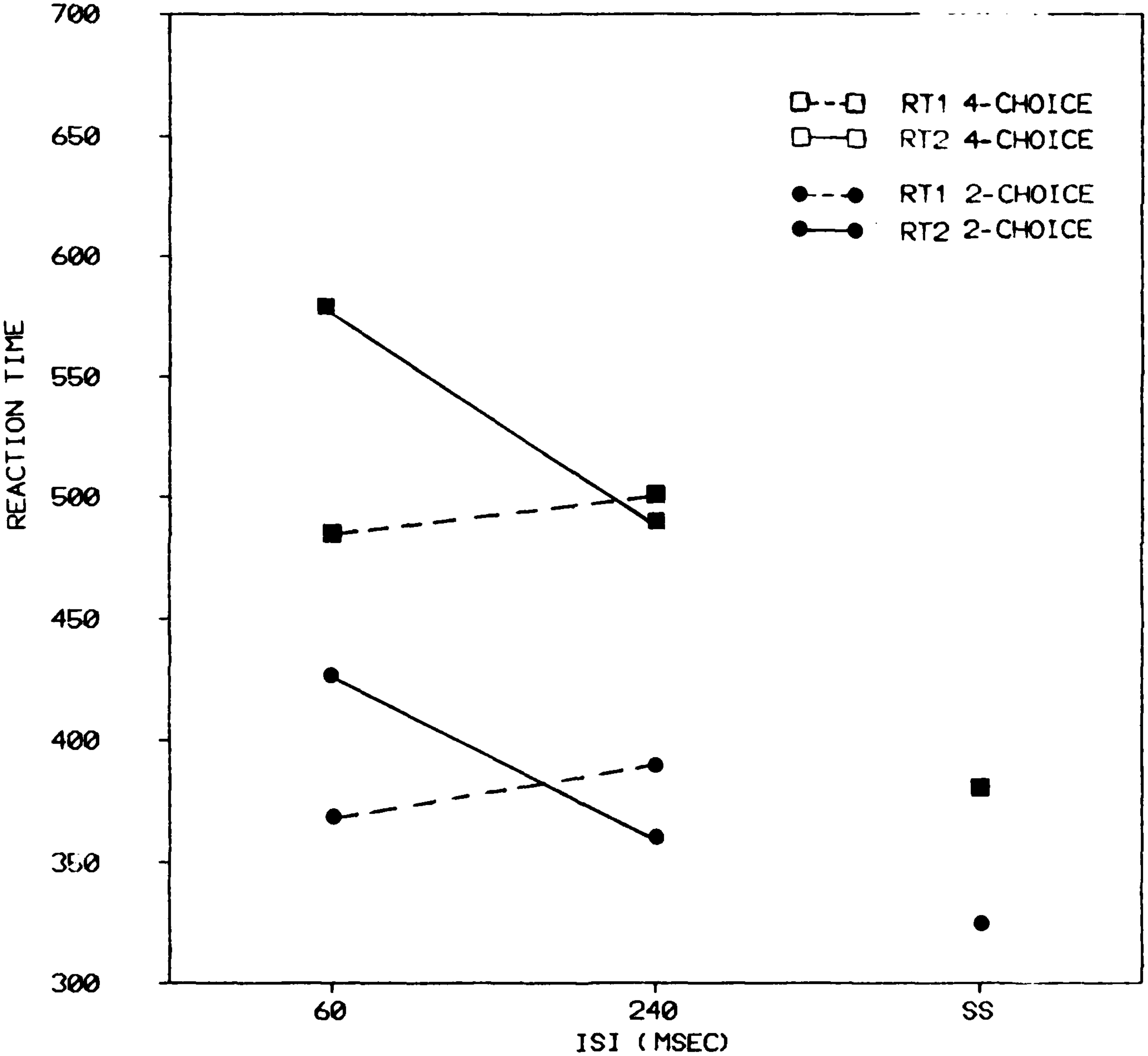


Figure 8. Mean reaction times for first and second responses.

For RT_1 effects of Choice were significant, $F(1,6) = 70.1$, $p<.001$, while effects of ISI, $F(1,6) = 1.47$, $p>.05$, were not. Both 2-choice, ts$(12) > 4.25$, $p>.01$, and 4-choice, ts$(12) > 9.12$, $p<.001$, double-stimulation conditions were elevated relative to their appropriate single-stimulation control condition. This set of results replicates the findings of Experiment 1.

Figure 9 shows accuracy as a function of number of choices and ISI. For R2 accuracy only the effect of Choices was significant, $F(1,6) = 10.6$, $p < .05$. For R1 accuracy no effects reached the .05 level of significance for double-stimulation conditions. For both R2, $F(2,12) = 1.41$, $p > .05$, and R1, $F(1,12) = 1.77$, $p < .05$, no differences were found between single- and double-stimulation conditions. Thus, as was the case for Experiment 1, speed-accuracy trade-off can be ruled out as an explanation of RT differences between single- and double-stimulation conditions.

Autonomic Measures

Figure 10 shows IBI standard deviation as a function of ISI and number of choices. No significant effects of ISI or Choice were obtained for mean IBI so there data are not displayed. For IBI standard deviation, effects of Choice were significant, $F(1,11) = 5.42$, $p<.05$ while effects of ISI were not. These results replicated findings of Experiment 1 for IBI standard deviation. Since Experiment 2 included mixed 2- and 4-choice trials in each block, it was not possible to perform a spectral analysis of Choice as was done for Experiment 1.

A spectral analysis was conducted for ISI but no significant effects were found for either log $\hat{V}_{RSA}$ or log $\hat{V}_{BP}$. This result is entirely consistent with the lack of a significant effect of ISI upon IBI standard deviation.

A marginal interaction between ISI and Choice is also displayed in Figure 10, $F(2,10) = 3.80$, $p < .06$. While the single-stimulation control condition showed no effect of Choice upon IBI standard deviation, as the task became more difficult by decreasing ISI, effects of Choice also increased.

Event-Related Potential

Coles, Gratton, Kramer, and Miller (in press) present a systematic account of the many ways in which EEG data can be analyzed. At the risk of squeezing their categorizations into a Procrustean bed we have assigned data reduction techniques into only two categories. Simple data reduction can be achieved by inspection of the averaged data and includes peak and area measurement. Sophisticated data reduction requires computational analyses and includes principal components analysis, linear stepwise descriminant analysis, and other multivariate techniques. Coles et al. make it quite clear that simple analyses

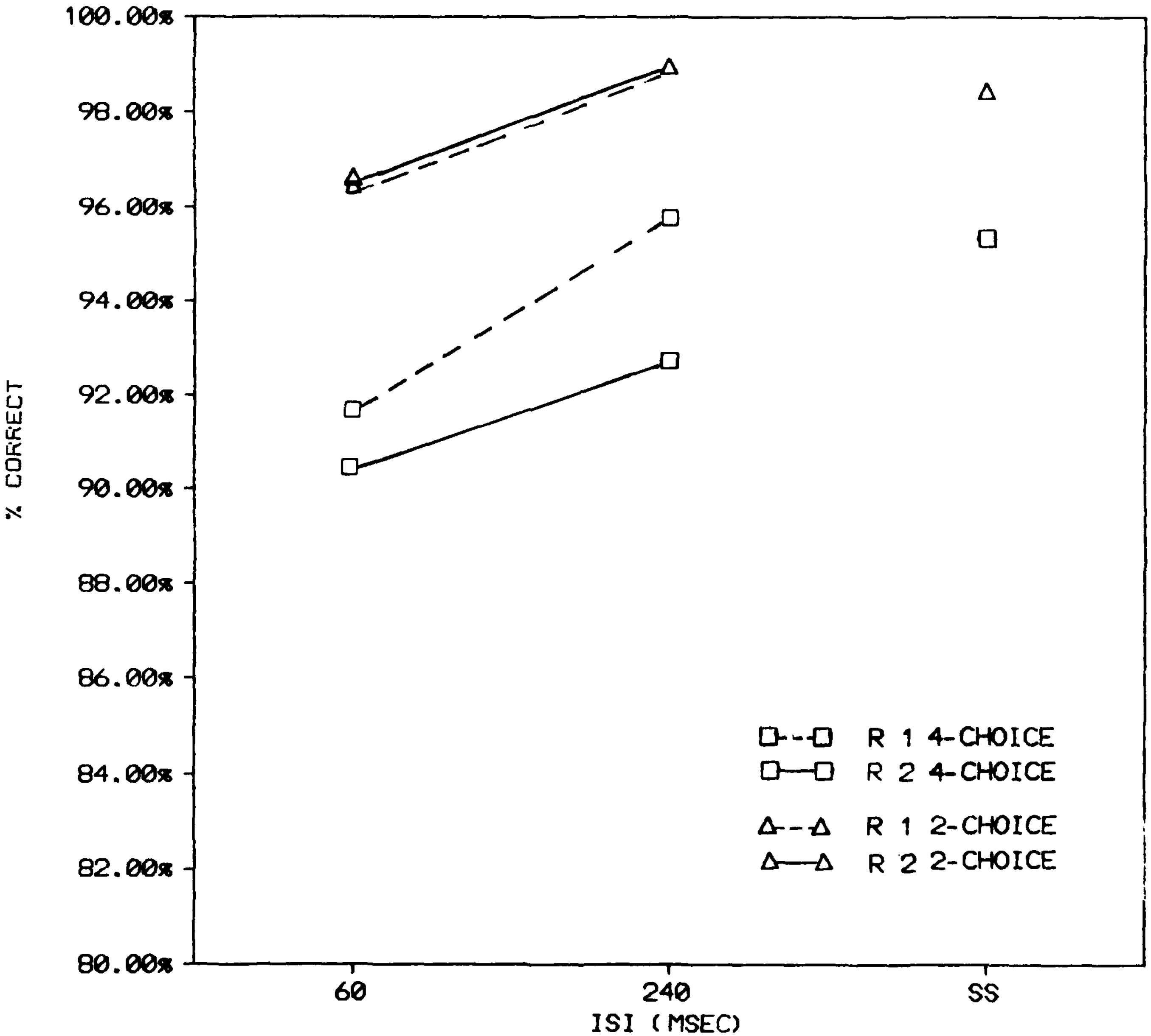


Figure 9. Mean accuracy for first and second responses.

Figure 10. Mean IBI standard deviation as a function of ISI.

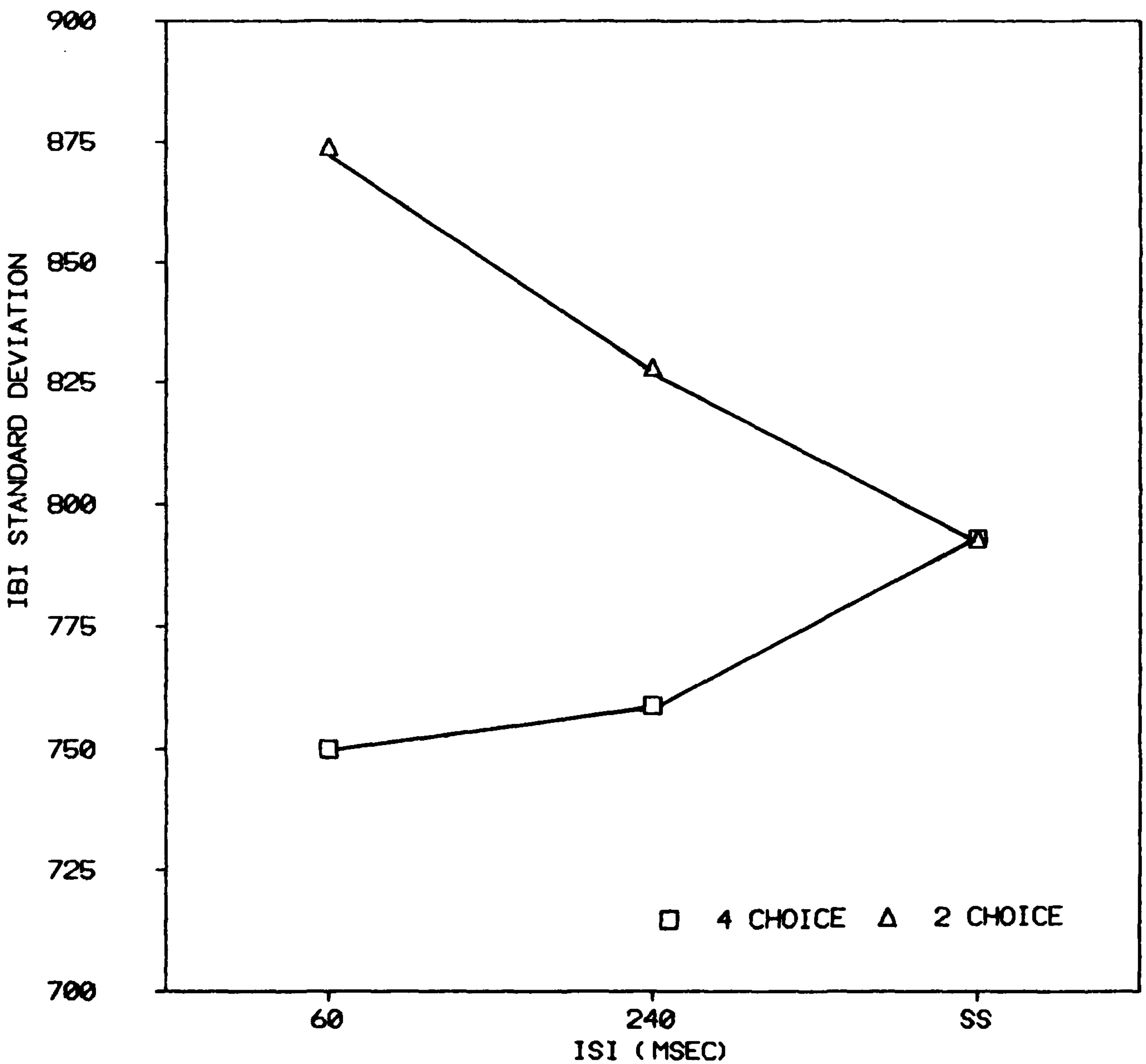


Figure 11. Grand means (N=6) ERP for 2-choice single-stimulation control condition. Pz is upper curve. Cz is lower curve. Positive is up.

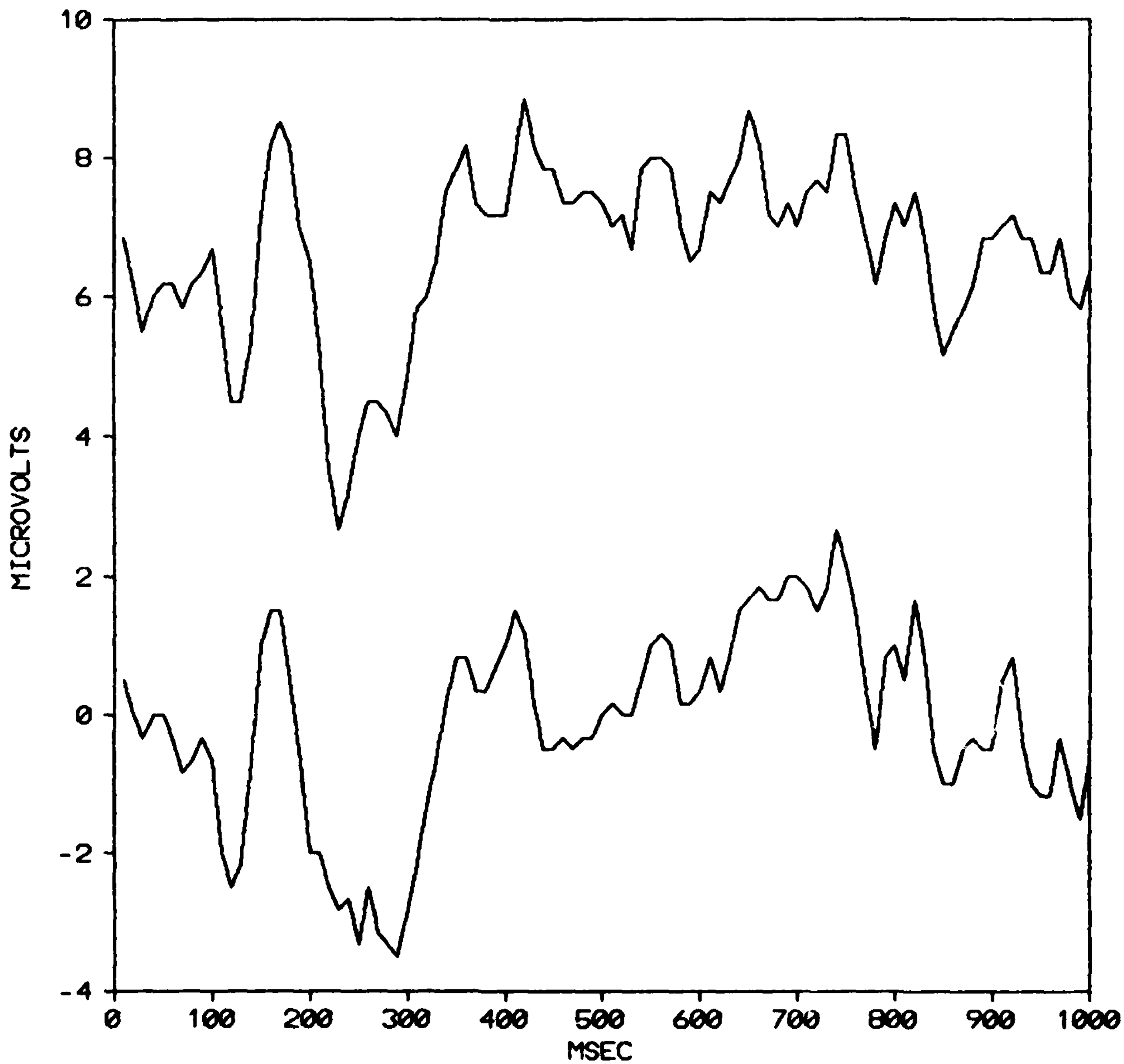


Figure 12. Grand means ERP for 2-choice 60 msec ISI.

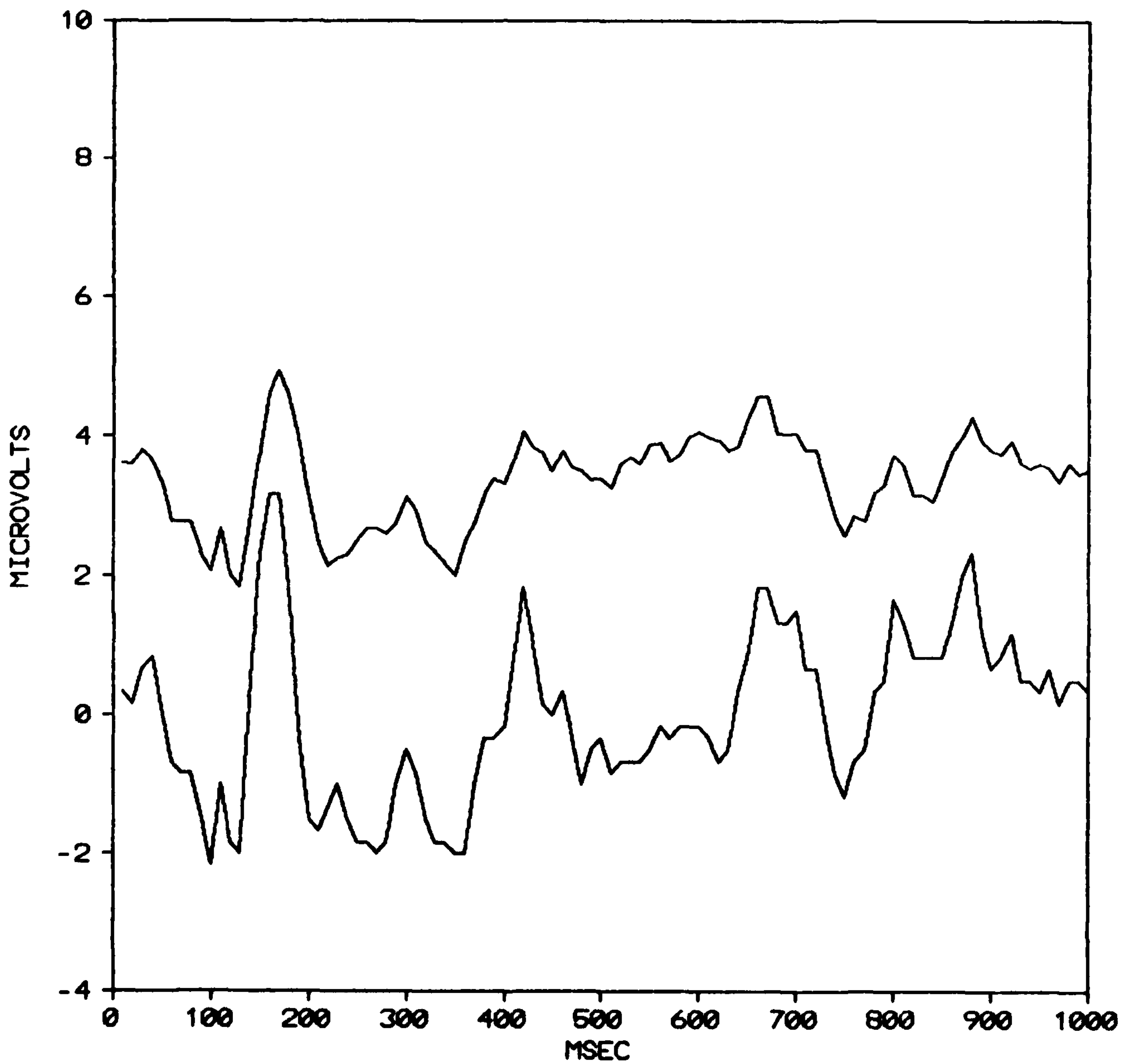


Figure 13. Grand means ERP for 2-choice 240 msec ISI.

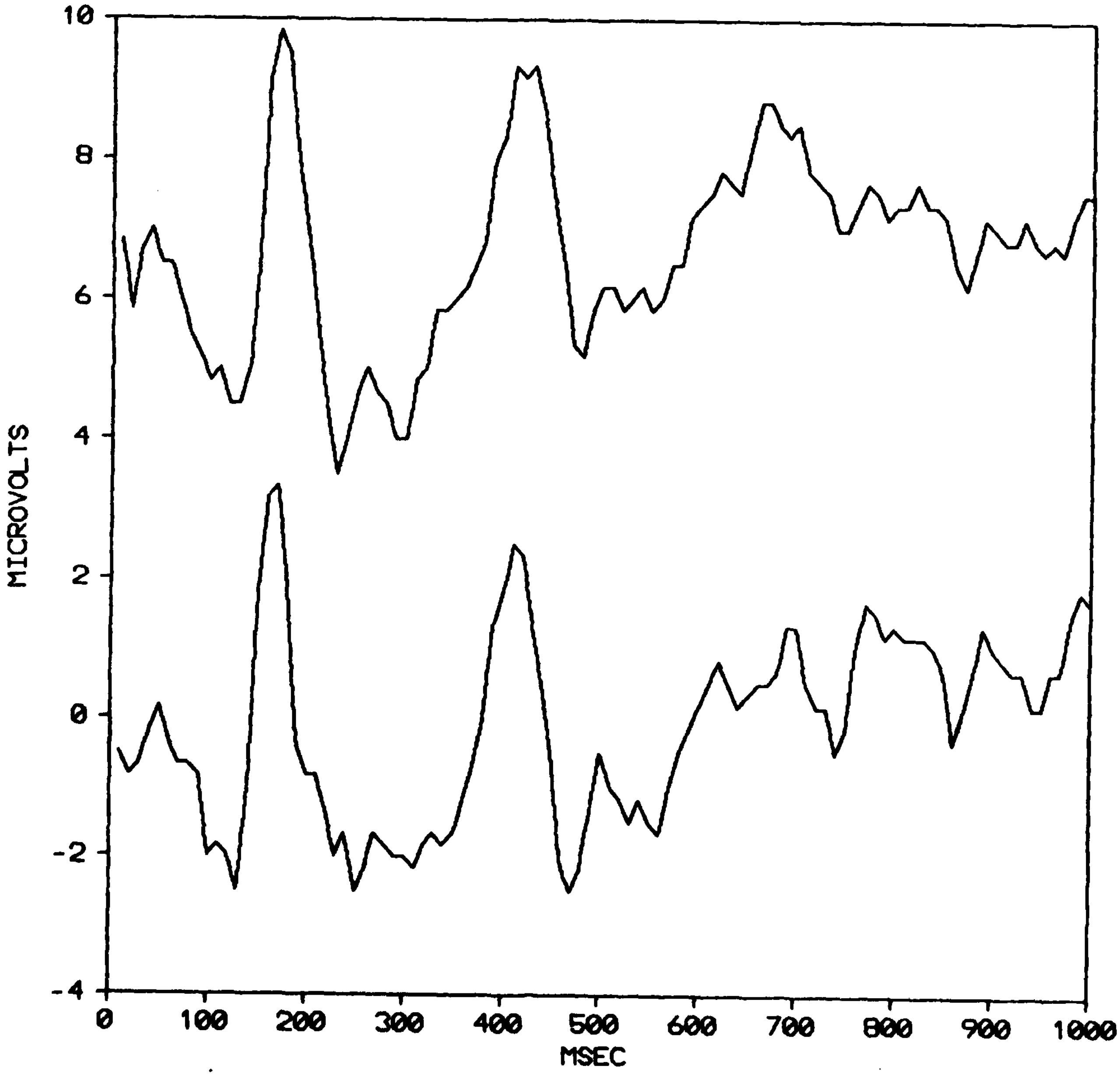


Figure 14. Grand means ERP for 4-choice single-stimulation control condition.

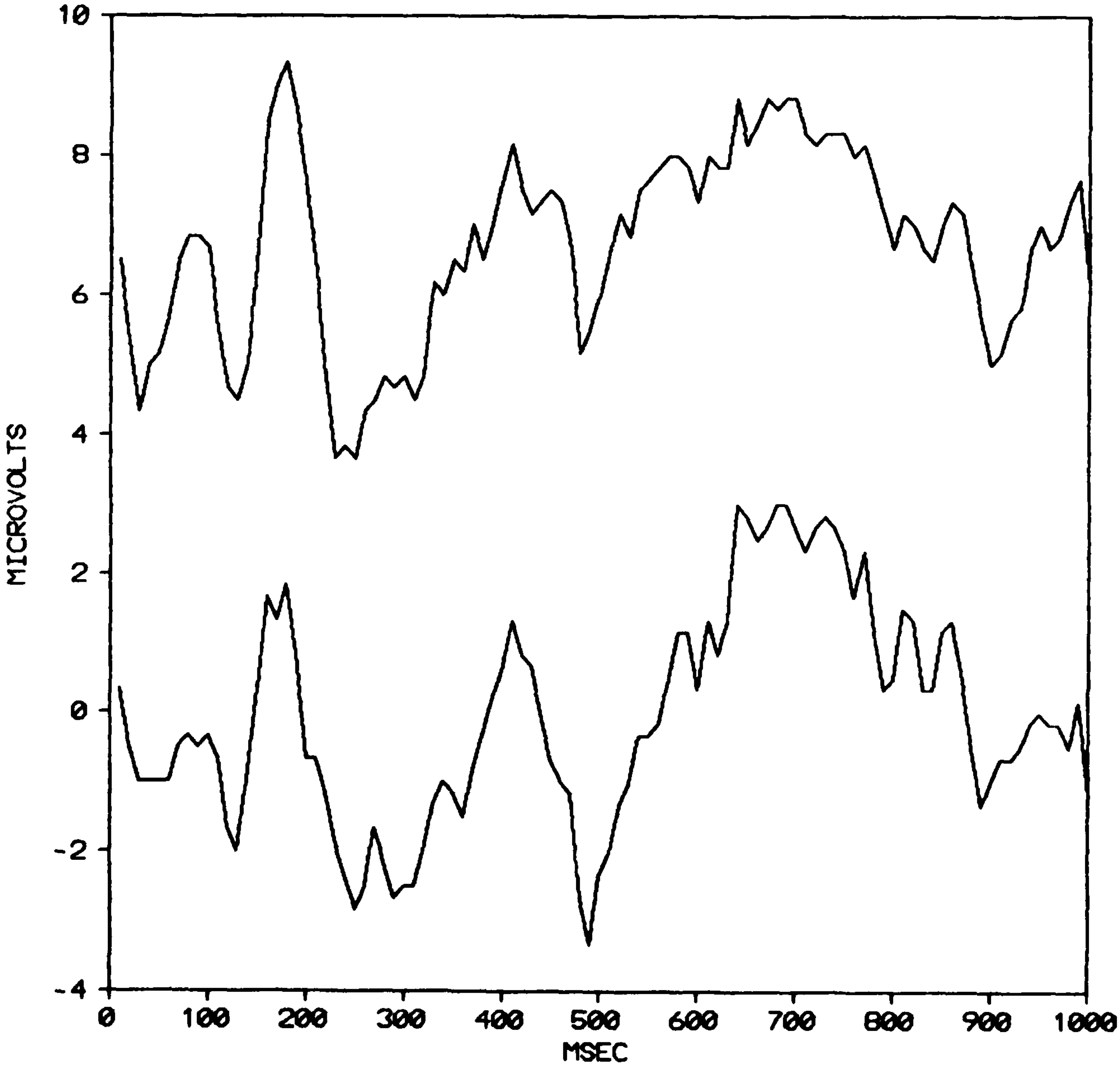


Figure 15. Grand means ERP for 4-choice 60 msec ISI.

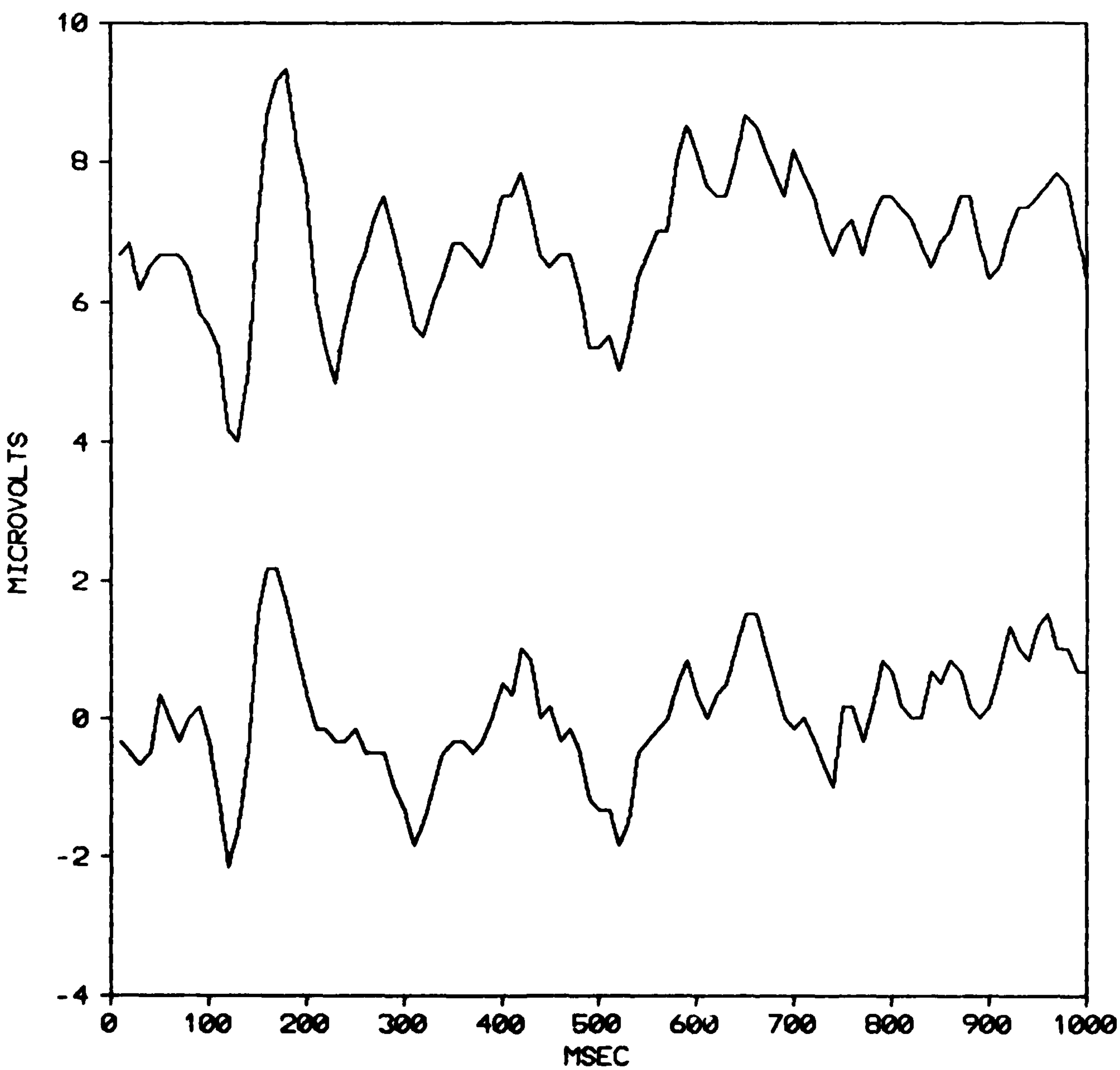
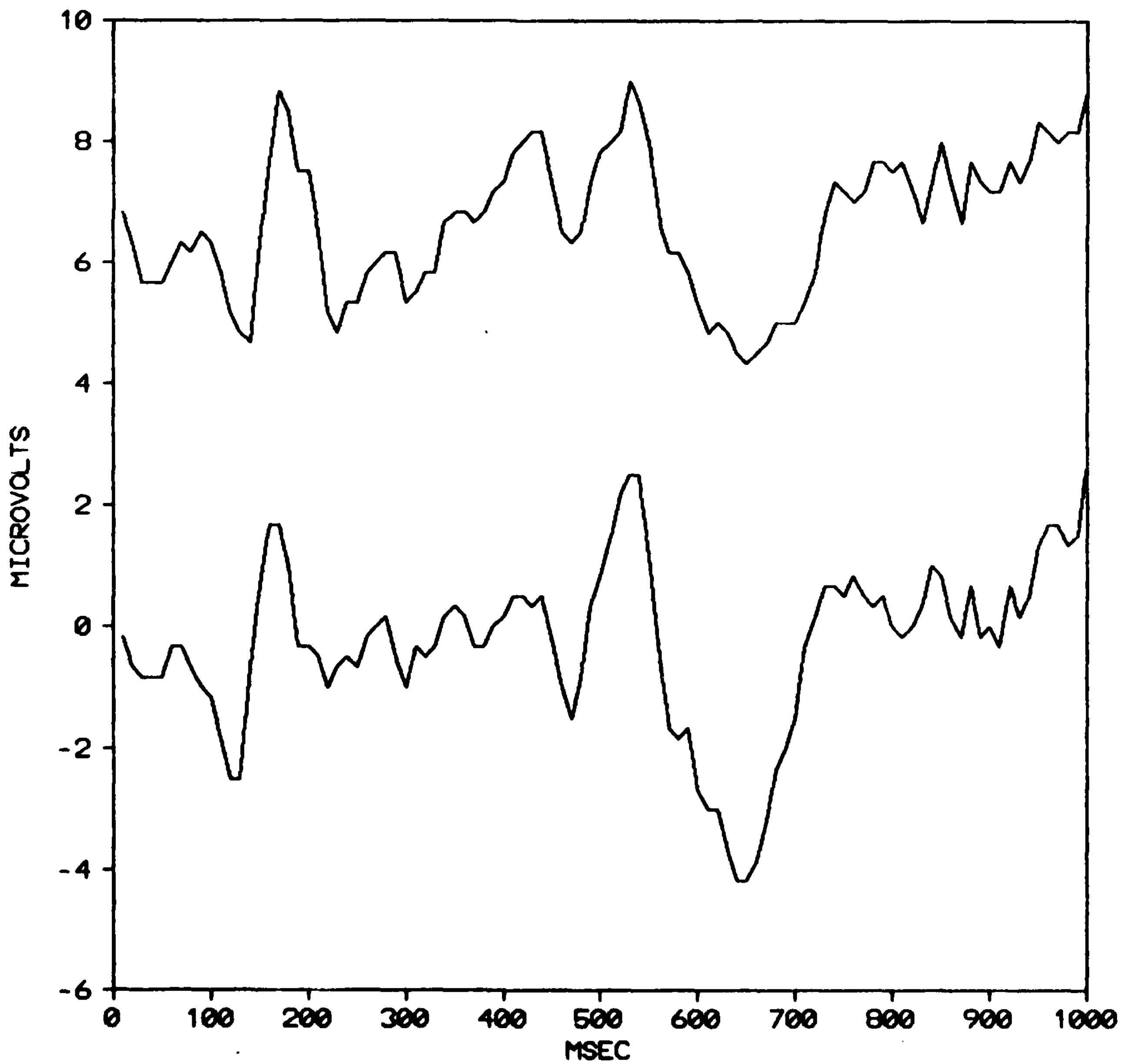


Figure 16. Grand means ERP for 4- choice 240 msec ISI.



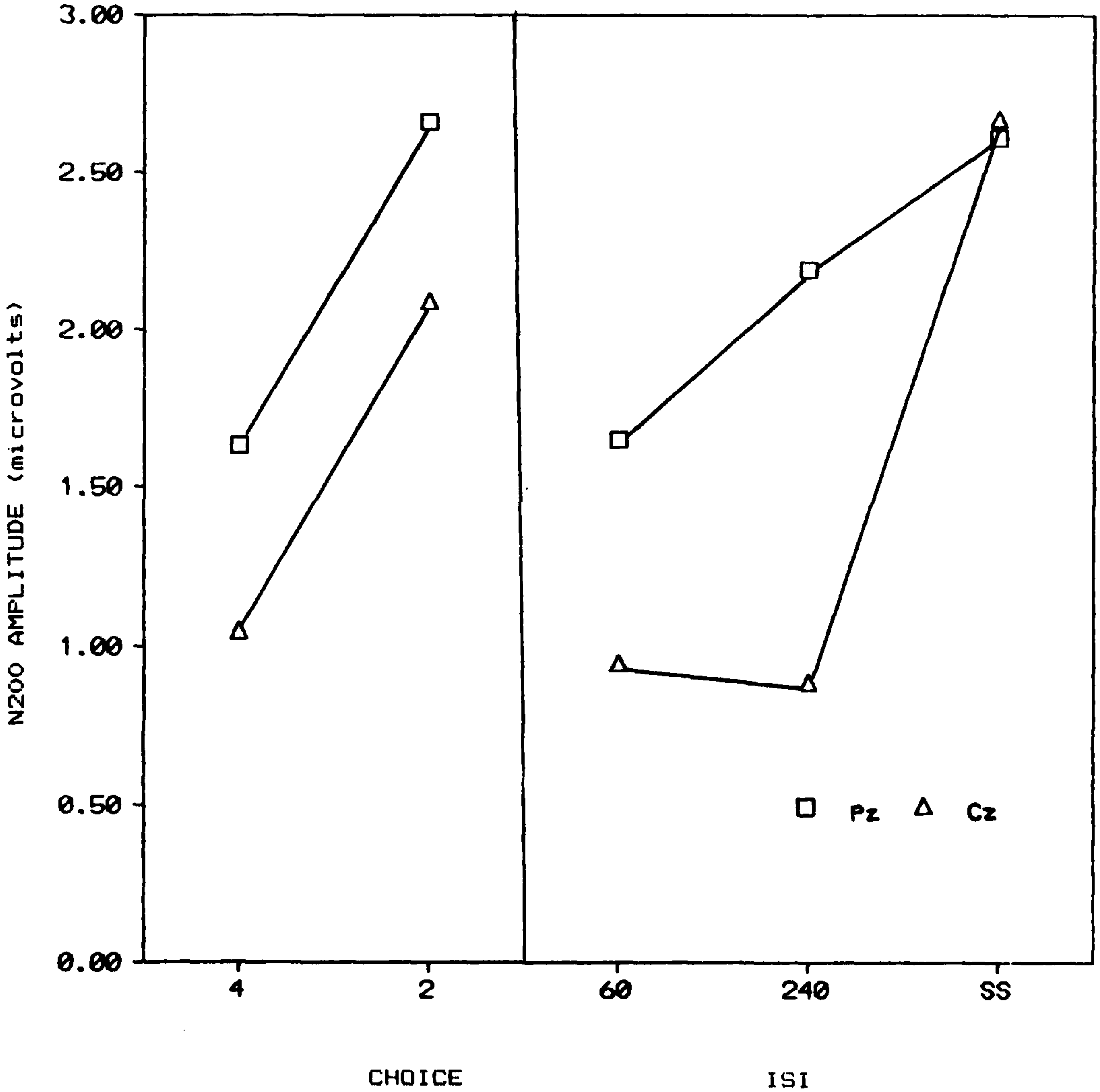


Figure 17. Grand mean N200 amplitude as a function of Choice and ISI.

ignore some of the information in the biocybernetic signal and so must be used with great caution. Sophisticated analyses are much to be preferred.

The short time period of Phase I did not permit sophisticated analyses. Hence, the preferred analyses must be deferred until Phase II. Figures 11 -16 present grand means for each combination of ISI and Choice. In all Figures, 5 microvolts has been added to the upper waveform to keep it from overwriting the lower waveform and so making the Figures difficult to read. Early components (N100-P200) are easily discerned in each figure. Furthermore, superposition of the figures reveals that latencies of these two components are identical for all figures.

Figure 17 shows N200 amplitude for Choice and ISI separately. For both Pz and Cz there is some indication that decreasing workload increases N200 amplitude. Thus, going from 4- to 2-choice results in approximately a one microvolt increase in N200 amplitude. A smooth increase in Pz occurs as ISI increases from 60 msec to single-stimulation control condition. There is an even greater increase in Cz, but the increase is entirely a step-function jump from double- to single-stimulation. While these increases may suggest that N200 amplitude is a viable index of workload, caution should be exercised in any interpretation until the sophisticated data analyses of Phase II are completed.

The differences that occur later in the waveforms are difficult to characterize precisely by only visual inspection. For example, the 240 msec ISI 4-choice condition shows a large late negative peak at about 650 msec that might be related to S2-R2 processing. The absence of a similar late negative peak for the 2-choice 240 msec ISI could be due to the certainty of S2 given S1 in that condition. This interpretation is consistent with the rapid RT_2 results reported above for the 2-choice condition. The possible migration of late components is difficult to establish visually. For example, a large positive peak at about 400 msec for 2-choice 240 msec ISI can be contrasted with a similar but slightly later peak at about 550 msec for 4-choice 240 msec ISI. While it seems reasonable that the additional uncertainty associated with the 4-choice condition would delay certain ERP components, this conclusion is not justified without sophisticated data reduction.

In a similar fashion, visual comparison can locate other differences, albeit less dramatic, than those noted above. But it seems premature to draw any conclusions just yet. This must await the more sophisticated analyses of Phase II. For now, all that can be claimed is that interesting differences appear to be manifest in the ERP but these cannot yet be reliably interpreted. Results do justify continued collection and sophisticated analysis of ERP data in Phase II.

CONCLUSIONS

The two experiments reported above satisfy the technical goals of Phase I research and give a firm foundation for continuing such efforts in Phase II. The behavioral data were precisely as expected: RT_2 increased with number of choices and decreased over ISI while RT_1 also increased with number of choices, was flat over ISI but elevated relative to its single-stimulation control condition. Thus, the psychological refractory period paradigm is an appropriate test bed for studying effects of workload in a controlled laboratory setting.

The biocybernetic measures also were indicants of operator workload. The autonomic measures also were as predicted: IBI standard deviation and spectral data were significantly lower for increased workload (2-choice vs 4-choice) but were not affected by ISI. In Experiment 1 mean IBI was also an indicant of workload associated with response information, but in general we would expect IBI standard deviation to be a preferred measure since mean IBI can be influenced by physical workload and emotional state. Event related potentials also were sensitive to workload: N200 amplitude was sensitive to information load as well as ISI. However, additional analysis in Phase II is required to bolster this tentative conclusion regarding ERP.

These findings can be related to the hybrid model (Figure 1) mentioned earlier. The behavioral data, of course, are consistent with the model since the model was in part designed to explain RT effects in double stimulation. The model assigned effects of Choice and ISI to stage 3. The biocybernetic data may eventually allow a finer-grained analysis of the model. For example, autonomic measures (IBI standard deviation and spectral data) were sensitive to only information load. Thus one might speculate that IBI variance is an index of the capacity supplied by the source to processing stages, especially stage 3. The N200 ERP component has been associated with an automatic mismatch process and its early component (MMN-mismatch negativity) can occur without a succeeding positivity (Naatanen & Gaillard, 1983). It is claimed that MMN is "only elicited by physical stimulus deviance" (op. cit., p. 131). This would imply that N200 is related to stages 1 and 2 of the hybrid model. However, since all stimuli were both physically identical and equiprobable in Experiment 2 it is not at all clear how this interpretation of N200 applies to the present results. Many speculations are possible. For example, N200 might be an index of mismatch between the actual physical stimulus that appeared on any given trial and an anticipated stimulus. This could be tested by comparing N200 for correct and error trials using a speeded deadline to increase error rates. (Error rates in Experiment 2 were too low for such an analysis.) This possibility will be evaluated during Phase II.

Finally, a comparison of workload effects for Experiment 1 versus Experiment 2 is of some interest. Experiment 2 used mixed 2- and 4-choice trials within blocks so that partial advance information supplied by the warning signal was useful. Thus operator workload was greater for Experiment 2 relative to Experiment 1 where no partial advance information had to be processed. IBI standard deviation was lower for Experiment 2 which is consistent with the greater workload.

In summary, it is clear that biocybernetic data are useful indicants of operator workload in a psychological refractory period task. Thus, it seems reasonable to speculate that biocybernetic data would prove equally useful in timesharing paradigms requiring simultaneous performance of independent tasks. A theoretical distinction between task difficulty and task complexity (Kantowitz, 1985) may be relevant. Task difficulty refers to the capacity demands of processing whereas task complexity refers to the architecture of internal information flow. It may be possible to show that IBI standard deviation is sensitive to manipulations of task difficulty but not of task complexity; this speculation is suggested by the present results where IBI standard deviation was influenced by information load but not by ISI. Timesharing paradigms permit a cleaner manipulation of task complexity than do psychological refractory period paradigms. In addition, ERP may index task complexity (and perhaps task difficulty as well). If biocybernetic variables could distinguish between manipulations of task difficulty versus manipulations of task complexity, experimenters would have an important methodological tool to build converging operations. A recent review of theory and methodology in attention, that did not discuss biocybernetic measures, concluded that capacity could be retained as a meaningful construct only if converging operations could be established (Kantowitz, 1985). Perhaps biocybernetic measures can provide such badly needed converging operations.

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